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MEMORANDUM REPORT NO. 2501

PRELIMINARY SURVEYS OF THE THREE DIMENSIONAL BOUNDARY LAYER ON A YAWED, SPINNING BODY OF REVOLUTION

Walter B. Sturek

July 1975

USA BALLISTIC RESEARCH LABORATORIES
ABERDEEN PROVING GROUND, MARYLAND

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER BRL Memorandum Report No. 2501	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PRELIMINARY SURVEYS OF THE THREE DIMENSIONAL BOUNDARY LAYER ON A YAWED, SPINNING BODY OF REVOLUTION		5. TYPE OF REPORT & PERIOD COVERED Final 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Walter B. Sturek		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS USA Ballistic Research Laboratories Aberdeen Proving Ground, Maryland 21005		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS RDT&E 1T161102A33D
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Materiel Command 5001 Eisenhower Avenue Alexandria, Virginia 22333		12. REPORT DATE JULY 1975 13. NUMBER OF PAGES 35
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Three-Dimensional Boundary Layer
Body of Revolution
Total Pressure Measurements
Flow Visualization
Compressible Flow
Magnus Effects
Spinning Model

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (lca)

Experimental measurements of the three dimensional boundary layer on a yawed, spinning tangent-ogive-cylinder model in supersonic flow are reported. The measurements were made using a flattened total head probe at one axial station near the base of the model for 10 azimuthal stations about the circumference. The test conditions were: M = 3, angle of attack = 4°, ω = 0 and 10,000 RPM. The trends observed in comparing measurements with and without the model spinning were: (1) the boundary layer is more thick (Cont.)

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20. ABSTRACT (Continued):

and less full where surface spin opposes the crossflow velocity; and (2) the boundary layer is less thick and more full where surface spin is in the same direction as the crossflow velocity.

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I. INTRODUCTION

Boundary layer development over a yawed, spinning body of revolution is of particular interest to the Army as applied to the design of artillery projectiles in general and in gaining further knowledge of the Magnus effect in particular. Reference 1 presents some experimental evidence showing the significant effect that the boundary layer configuration has on the Magnus force experienced by a yawed, spinning body of revolution as well as a discussion of the influence of Magnus on the aerodynamic stability of a spin stabilized projectile. Boundary layer development over non-spinning bodies of revolution is also of interest to the Army in the aerodynamics of missiles.

Recent advances in computational fluid dynamics have resulted in increased effort toward computation of three dimensional boundary layer development. The computations published to date that have come to the author's attention have included only laminar boundary layers in compressible flow and both laminar and turbulent boundary layers in incompressible flow. References 2 to 5 give a partial listing of recent

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1. *W. B. Sturek, "Boundary Layer Studies on Spinning Bodies of Revolution," BRL Memorandum Report No. 2381, U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, May 1974. AD 920069L.*

2. *H. A. Dwyer, "Three Dimensional Flow Studies Over a Spinning Cone at Angle of Attack," BRL Contract Report No. 137, U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, February 1974. AD 774795.*

3. *H. A. Dwyer, "Boundary Layer on a Hypersonic Sharp Cone at Small Angle of Attack," AIAA Journal, Vol. 9, No. 2, February 1971, pp. 227-284.*

4. *T. C. Lin and S. G. Rubin, "Viscous Flow Over Spinning Cones at Angle of Attack," AIAA Journal, Vol. 12, No. 7, July 1974, pp. 965-974.*

5. *T. K. Fannelop and D. A. Humphreys, "A Simple Finite-Difference Method for Solving the Three Dimensional Turbulent Boundary Layer Equations," AIAA Paper No. 74-13, AIAA 12th Aerospace Sciences Meeting, January 1974.*

computation efforts, and References 6 to 10 are a representative listing of three-dimensional experimental investigations. For supersonic flow, the computations and experimental data are almost exclusively limited to a cone model. Two very recent publications, Dwyer[2] and Lin and Rubin[4], have shown very promising results that include the effects of surface spin for a yawed cone in supersonic flow. However, since it is almost impossible to obtain measurements of the laminar boundary layer on a cone in supersonic flow due to the small thickness of the viscous layer and the difficulty experienced in maintaining a laminar boundary layer over the complete model surface, there are no experimental data available to make a useful comparison to the computations.

The objective of this experimental effort is to obtain detailed boundary layer profile data that will be useful for comparisons with theoretical computations of three dimensional boundary layer development. As a first step, this report describes preliminary total head measurements of the boundary layer on a yawed, tangent-ogive-cylinder model. Measurements were made with the model spinning at a rate of 10,000 RPM and also while the model was not spinning. These measurements were made at one axial position near the base of the model for several azimuthal stations around the circumference of the model.

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6. *J. B. Morton, I. D. Jacobson, and Seldon Sanders, "Experimental Investigation of the Boundary Layer on a Rotating Cylinder," BRL Contract Report No. 185, U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, October 1974. AD B000138L.*

7. *H. Carl Thorman, "Boundary Layer Measurements on an Axisymmetric Body With Spin and Yaw," Master's Thesis, California Institute of Technology, November 1957.*

8. *H. R. Vaughn and O. L. George, "The Characteristics of a Laminar Boundary Layer on a Spinning Tangent Ogive Cylinder at Angle of Attack," Sandia Laboratories Report SC-RR-71 0851, Sandia Laboratories, Albuquerque, New Mexico, March 1972.*

9. *M. C. Fischer and L. M. Weinstein, "Turbulent Compressible Three-Dimensional Mean Flow Properties," AIAA Journal, Vol. 12, No. 2, February 1974, pp. 131-132.*

10. *W. J. Rainbird, "Turbulent Boundary-Layer Growth and Separation on a Yawed Cone," AIAA Journal, Vol. 6, No. 12, December 1968, pp. 2410-2416.*

II. THE EXPERIMENT

A. Test Facility

The tests were run in the BRL Supersonic Wind Tunnel No. 1[11]. This is a symmetric, continuous flow, closed circuit facility with a flexible plate nozzle. The test section has a height of 38 cm and a width of 33 cm. The nominal tunnel operating conditions were M = 3.0, $p_o = 0.299 \times 10^6$ Pa, and $T_o = 308°K$. The total pressure was maintained within ± 0.4 percent and the total temperature was controlled within ± 1°K during each individual test run.

B. Model

The model used was a seven caliber long tangent-ogive-cylinder with a one-caliber ogive section. The diameter of the model was 5.08 cm. A view of the model mounted in the test section is shown in Figure 1. The model was suspended on ball bearings and an internal air driven turbine was used to drive the model in spin. The model was made of high strength aluminum alloy and was highly polished. The model was dynamically balanced to a tolerance of 2.1 gram-cm.

C. Survey Mechanism

The survey mechanism, shown installed with the model in Figure 1, was designed to drive the probe perpendicular to the axis of the model. The probe is positioned by a cam that is rotated using the roll head mechanism. Since the survey mechanism is attached to the angle of attack crescent, the probe is driven perpendicular to the axis of the model for any angle of attack setting. The azimuthal position is determined by selecting predrilled mounting holes placed at 30° increments. The positions, $\phi = 90°$ and 270°, could not be surveyed due to a mechanical limitation of the mount.

The survey mechanism was calibrated by using a dial indicator to indicate the displacement of the probe support in thousandths of an inch to establish a table of displacement versus electrical output signal from the roll head mechanism. In the data reduction procedure divided difference interpolation was used to determine the y position for a given electrical signal. The coordinate system is indicated in Figure 2.

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11. *J. C. McMullen, "Wind Tunnel Testing Facilities at the Ballistic Research Laboratories," BRL Memorandum Report No. 1292, U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, July 1960. AD 244180.*

D. Test Procedure

Total head surveys were made of the boundary layer one-half caliber from the base of the model for an angle of attack of 4°, M = 3, and for spin rates of zero and 10,000 RPM. The surveys were made for azimuthal positions of $\phi = 0°$, 30°, 60°, 120°, 150°, 180°, 210°, 240°, 300°, and 330°. A spark shadowgraph showing the model with the total head probe positioned beyond the boundary layer is shown in Figure 3. The boundary layer was allowed to develop naturally (no trip was used). As shown in Figure 3, the boundary layer was turbulent on the lee-side and relatively thick. On the wind-side, transition to turbulence occurred close to the measuring station. This resulted in a large difference in thickness of the boundary layer from the wind to the lee-side.

The surveys were made by starting the measurements well beyond the edge of the boundary layer--at $y \sim 1.25$ cm whereas the largest δ was about 0.65 cm. The pressure signal from the total head probe was measured using a strain gage transducer that was calibrated within ± 0.25 percent of its full scale range--0-25 psi ($0\text{-}0.172 \times 10^6$ Pa). Measurements were made while holding the probe in a fixed position after allowing approximately thirty seconds for the pressure signal to stabilize. The position of the model surface was detected by electrical signal when the probe contacted the model surface when the model was not spinning. Immediately following the survey for the model not spinning, the model was spun to 10,000 RPM and another survey made again starting from well beyond the outer edge of the viscous region. The model spin was held constant within ± 200 RPM during the survey. These surveys were stopped close to, but not touching, the model surface in order to preclude damage to the model surface or the total head probe.

The total head probe used had a flattened tip. The probe tip had an opening of 0.076 mm with a lip thickness of 0.025 mm and was 2.5 mm in width. The probe was positioned to measure the pressure along lines parallel to the model axis.

III. DISCUSSION OF THE RESULTS

An attempt was made to measure the static pressure through the boundary layer; however, the results were considered unsatisfactory due to angle of attack sensitivity of the probe. Since no satisfactory measurement of the static pressure was available, the data could not be reduced to obtain the velocity in the boundary layer. For this reason, the data are presented as profiles of total pressure normalized by the total pressure external to the boundary layer. Examples of the measured profiles are shown in Figures 4 to 12. The consistency of the profile measurements is indicated in Figure 5 where individual data points are plotted for one of the profiles.

Figure 4 shows a comparison of the profiles obtained on the wind and the lee-sides. These profiles clearly show the large difference in thickness of the boundary layer from the wind to the lee-side. It is also seen that there is a substantial difference in the profiles at $\phi = 180°$ for $\omega = 0$ compared to $\omega = 10{,}000$ RPM. In this case, the profile for $\omega > 0$ is less thick and more full than that for $\omega = 0$. In examining the profiles at other azimuthal stations, it is seen that the profiles for $\omega = 0$ are more full for $\phi = 0°, 30°, 60°, 120°$, and $150°$. At all other azimuthal stations, the profiles for $\omega > 0$ are more full. The trends indicated here are: (1) the boundary layer is more thick and less full where surface spin opposes the crossflow velocity; and (2) the boundary layer is less thick and more full where surface spin is in the same direction as the crossflow velocity.

For the profiles at $\phi = 0°, 30°$, and $330°$, there is an overshoot in the total pressure near the edge of the viscous layer. This overshoot could be an indication of the formation of lee-side vortices which are fed from the wind-side inviscid flow. Another possibility is that the presence of the probe causes the very thin boundary layer to separate. Oil flow visualization was used in an effort to gain insight as to the cause of this overshoot. Pictures of the oil flow obtained are shown in Figures 13 through 15.

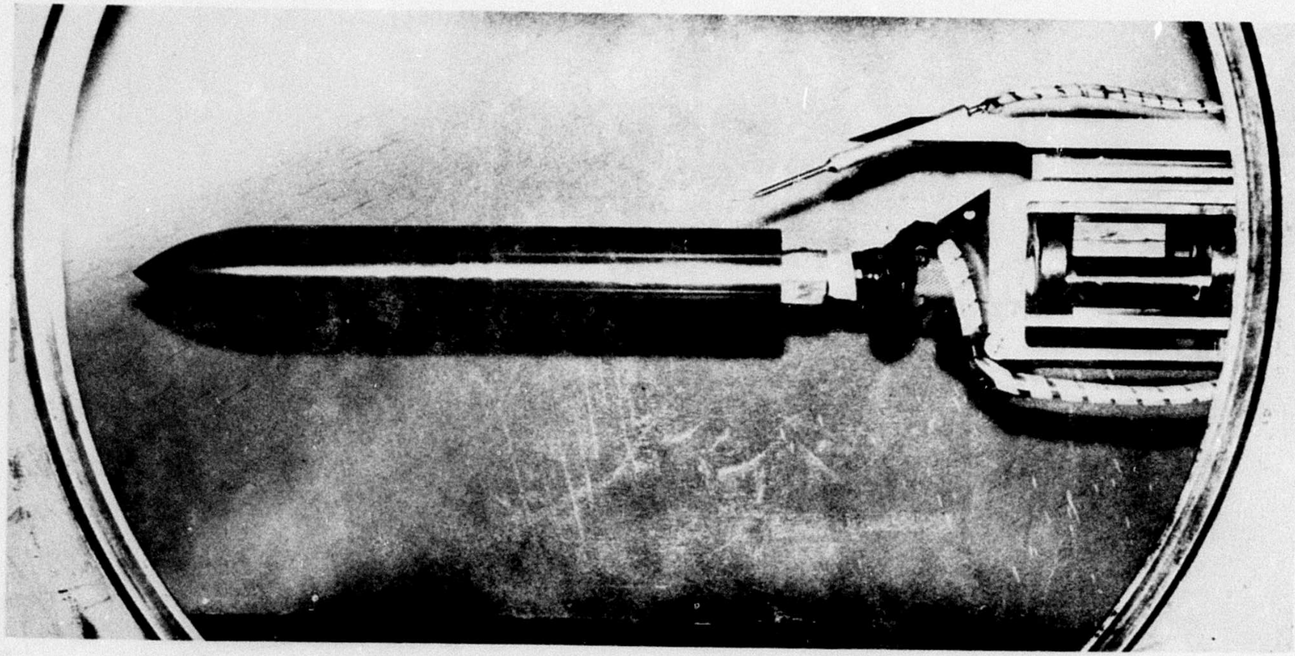
The oil flow pattern was obtained by painting the entire model with a thin coating of a mixture of T_iO_2 and Dow Corning 200 Fluid. The model was held non-spinning at 4° angle of attack for about fifteen minutes after flow was started in order for the oil pattern to become fully established. The pictures were made after the tunnel was shut down and with the model at $\alpha = 0°$. The model was positioned at 90° increments in azimuth in order to obtain views over the complete surface of the model. The pictures reveal the presence of high surface shear along the windward ray, wrapping up around the sides of the model as the flow develops toward the base. The unexpected appearance of a slender vortical streamer developing near the tip of the model and wrapping around to the lee-side at about the midlength of the model is also indicated.

These oil flow patterns strongly suggest the presence of vortex filaments submerged within the boundary layer on the lee-side near the base; however, the reason for the presence of the overshoot detected in the boundary layer surveys on the wind-side is not explained. Local boundary layer separation due to the presence of the probe is, however, considered to be less likely a cause for the shape of the total head profile than the presence of vortex filaments.

IV. CONCLUDING REMARKS

An experimental investigation to measure the boundary layer on a yawed, spinning ogive cylinder model in supersonic flow has been reported. Measurements were made using a flattened total head probe at one axial station, one-half caliber from the base of the model for ten azimuthal stations about the circumference of the model. Comparison of the profiles for ω = 10,000 RPM to those for ω = 0 revealed substantial differences. The trends indicated were: (1) the boundary layer is more thick and less full where surface spin opposes the crossflow velocity; and (2) the boundary layer is less thick and more full where surface spin is in the same direction as the crossflow velocity.

These data were obtained for the purpose of comparison with analytical or numerical computations of three-dimensional boundary-layer development. The data reported here are of a preliminary nature and are insufficient for a meaningful comparison with a theoretical analysis. In future experiments profile data will be obtained at several streamwise stations for a tripped turbulent boundary layer. Measurements will also be obtained of the wall static pressure using a non-spinning model instrumented with wall pressure taps.



THREE DIMENSIONAL
BOUNDARY-LAYER SURVEY
TANGENT-OGIVE-CYLINDER MODEL

Figure 1. Model and Survey Mechanism in Test Section

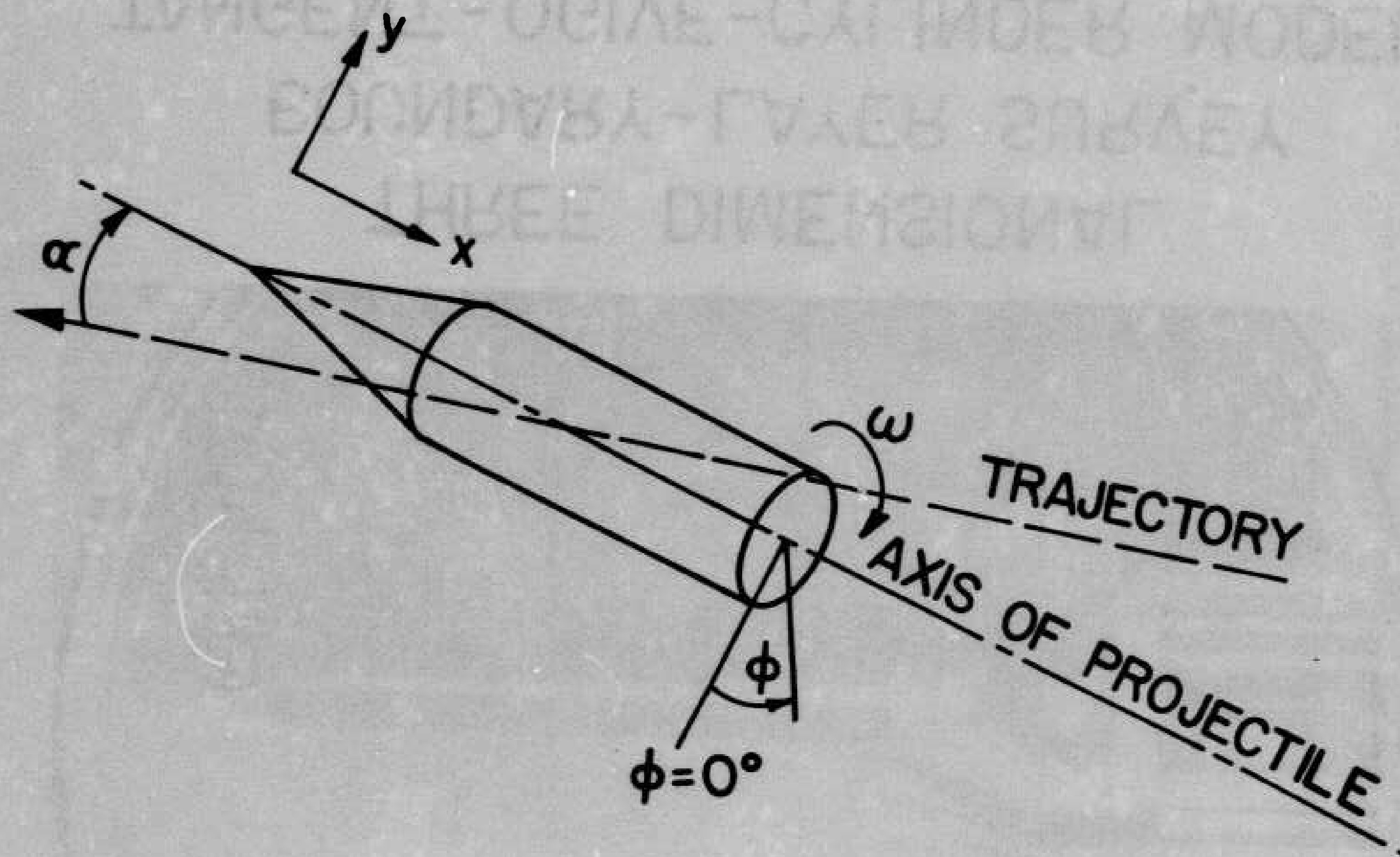


Figure 2. Coordinate System

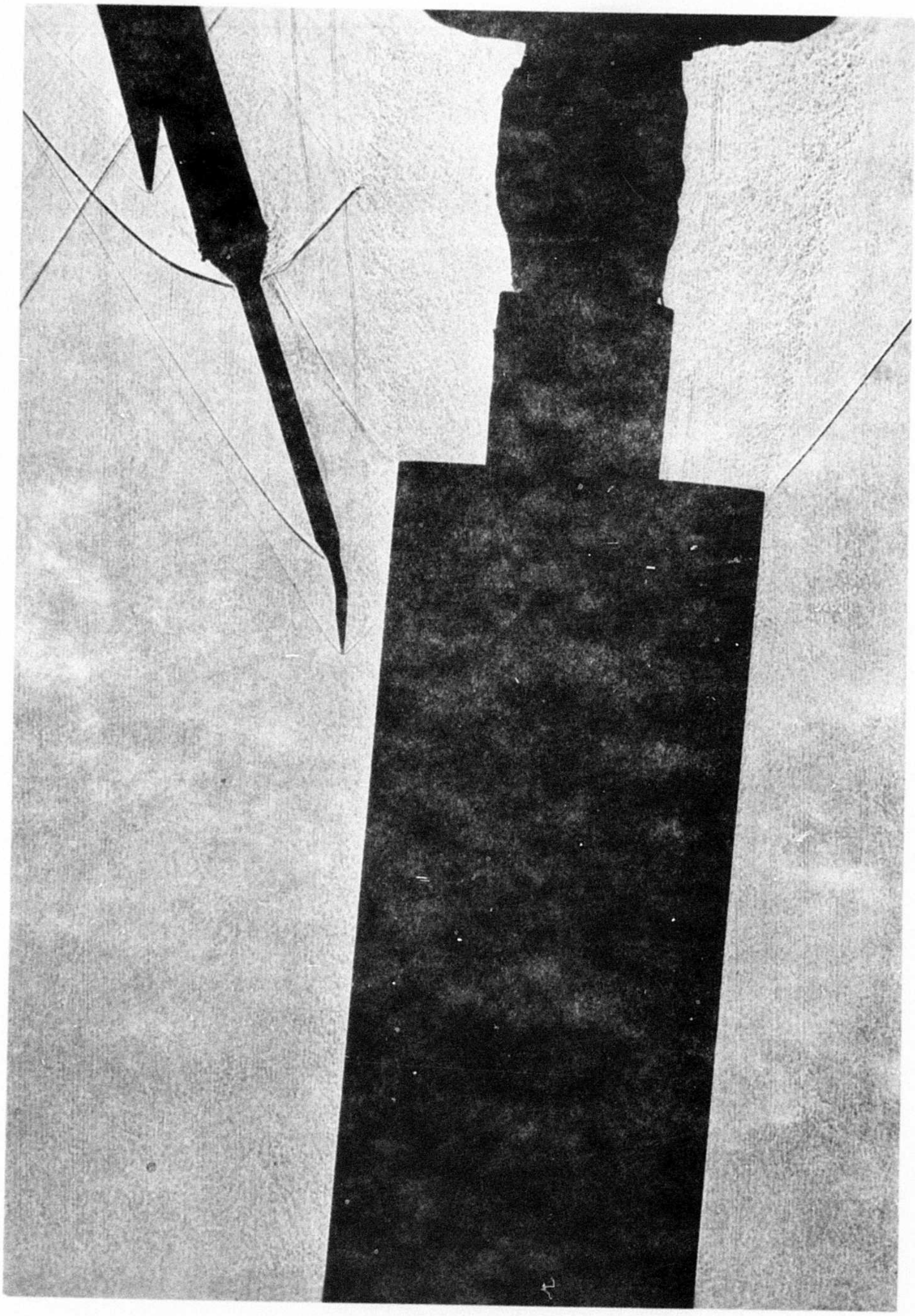


Figure 3. Spark Shadowgraph of Flow--Total Head Probe
Positioned Beyond Edge of Boundary Layer

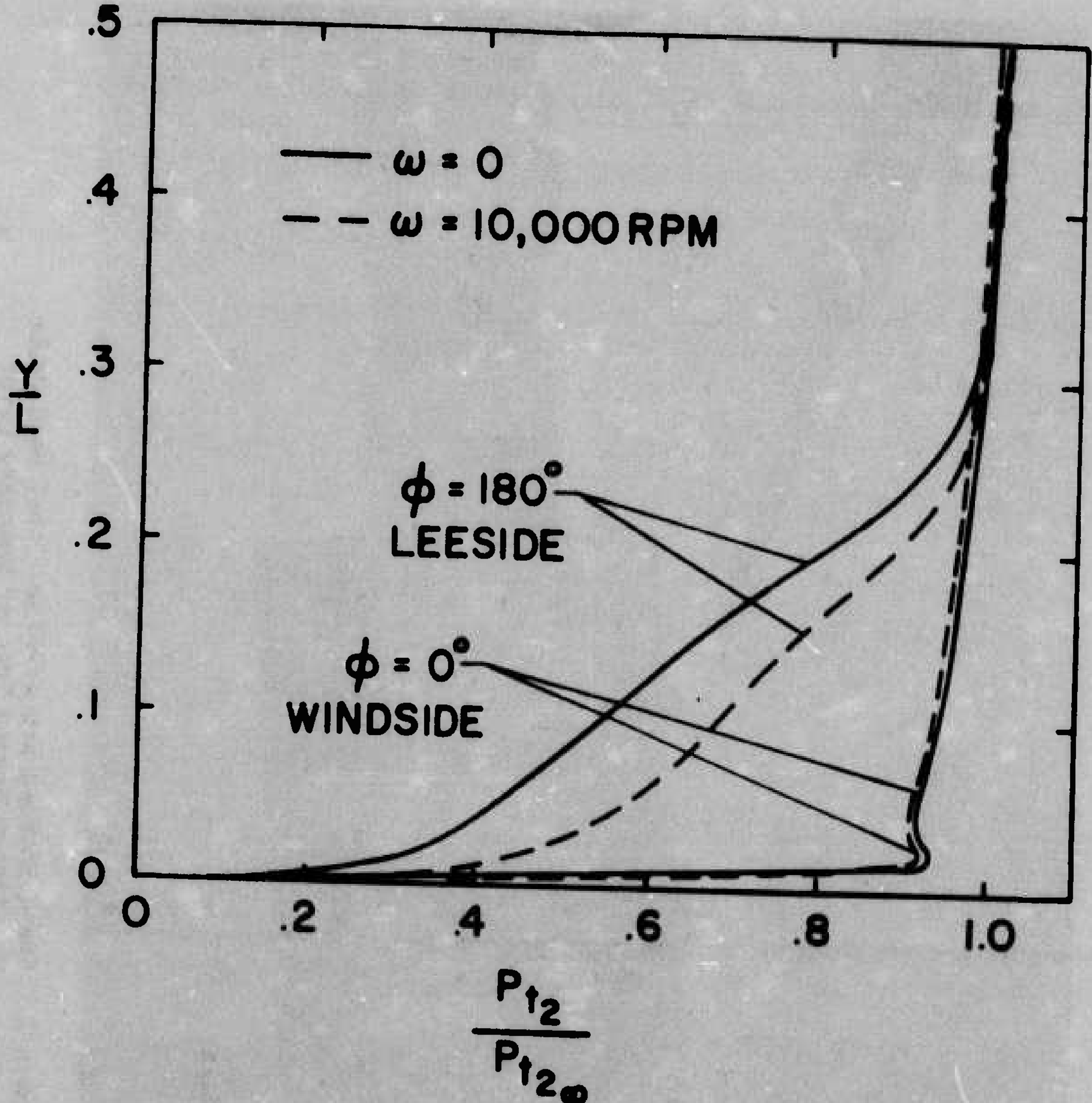


Figure 4. p_{t_2} Profiles--Wind and Lee Side

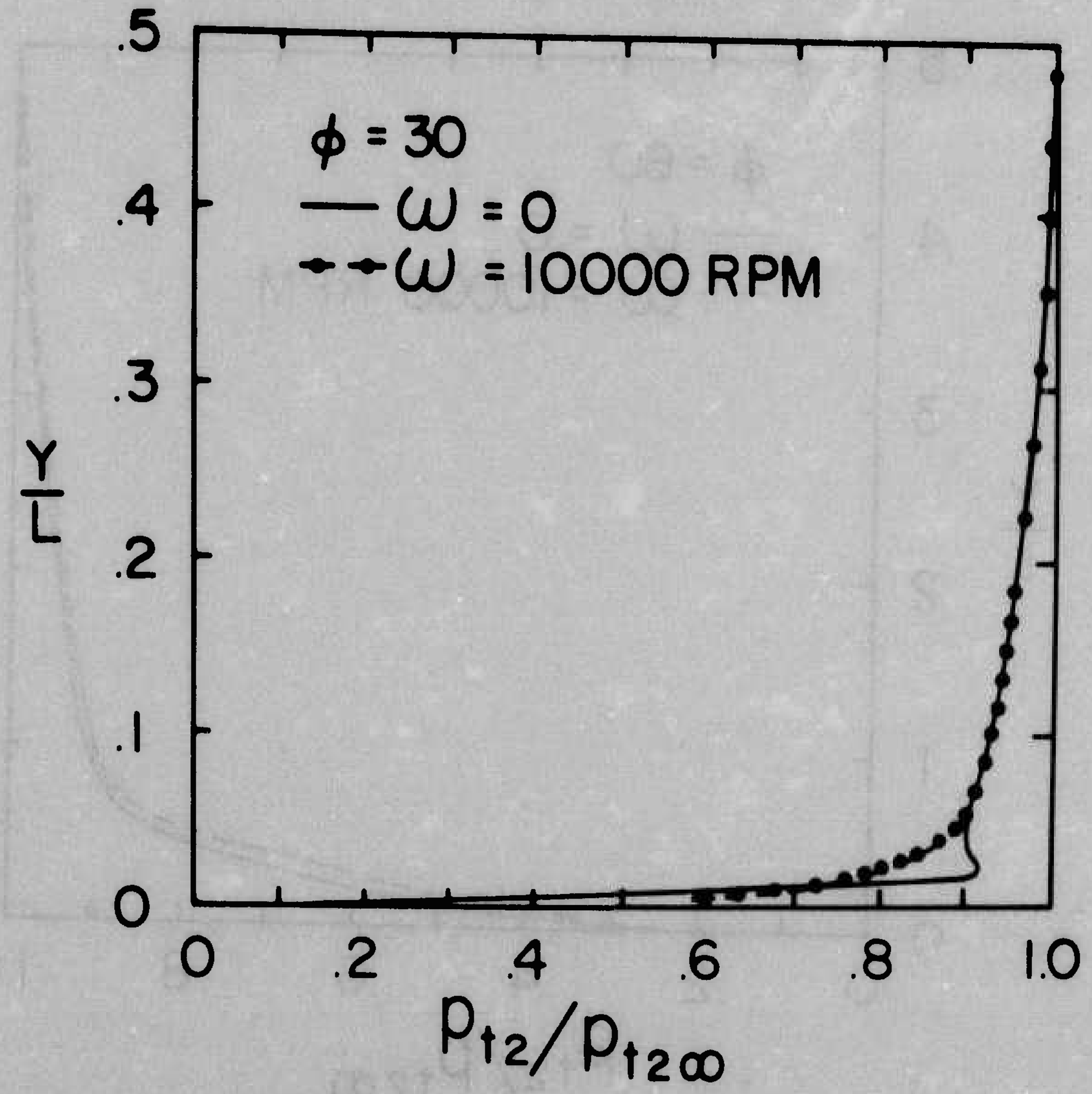


Figure 5. p_{t_2} Profiles, ϕ = 30

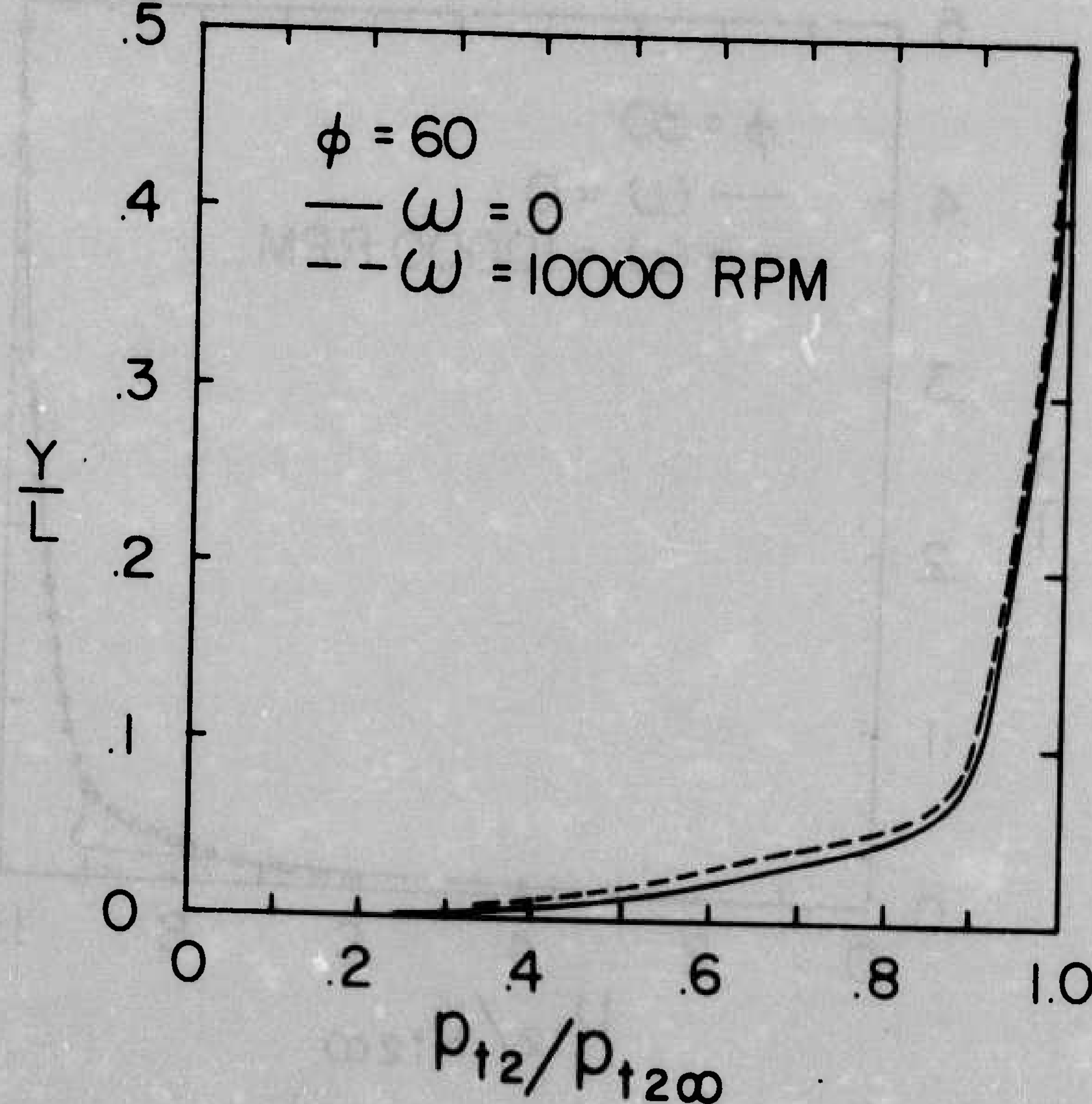


Figure 6. p_{t_2} Profiles, $\phi = 60$

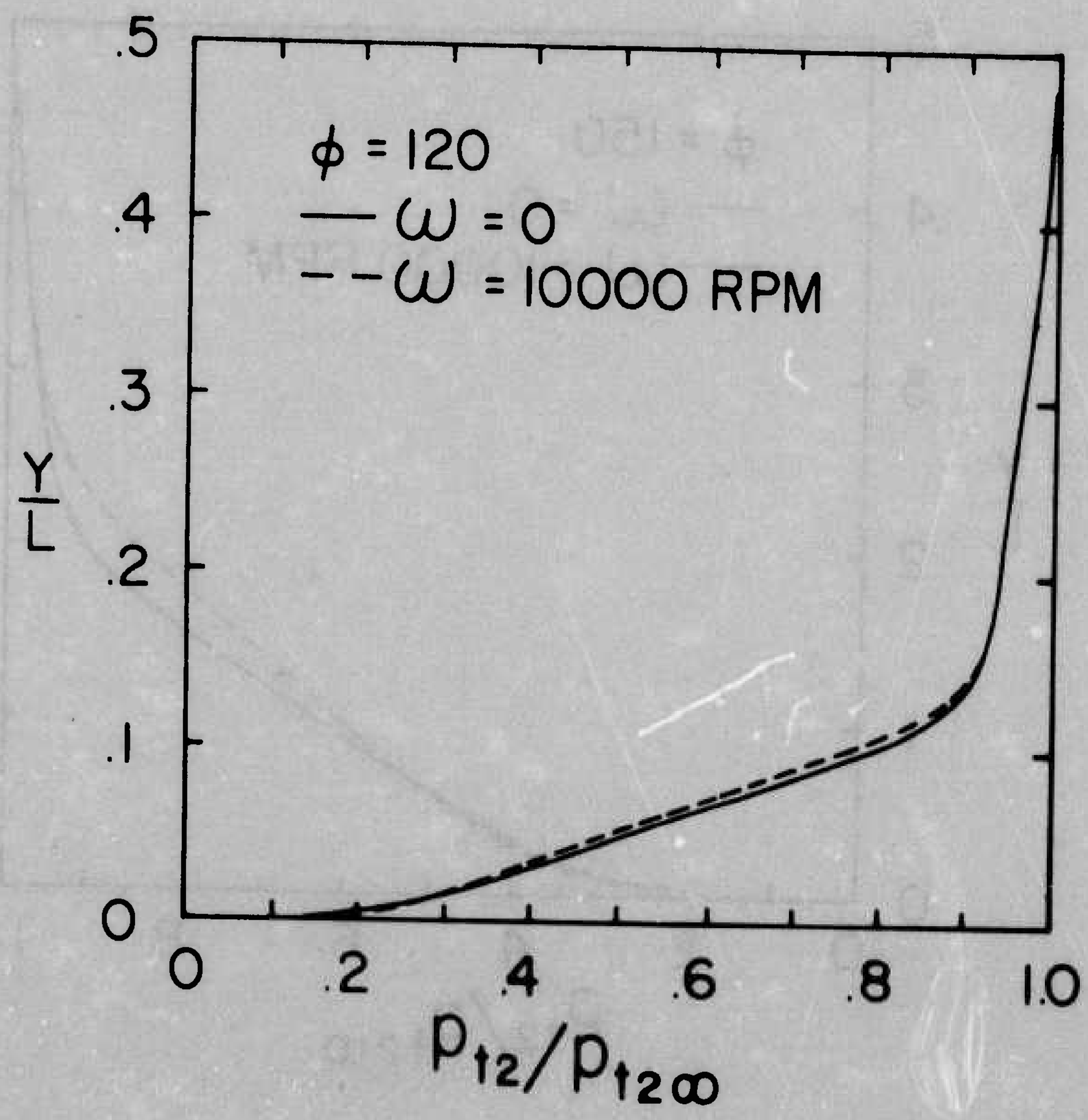


Figure 7. p_{t_2} Profiles, ϕ = 120

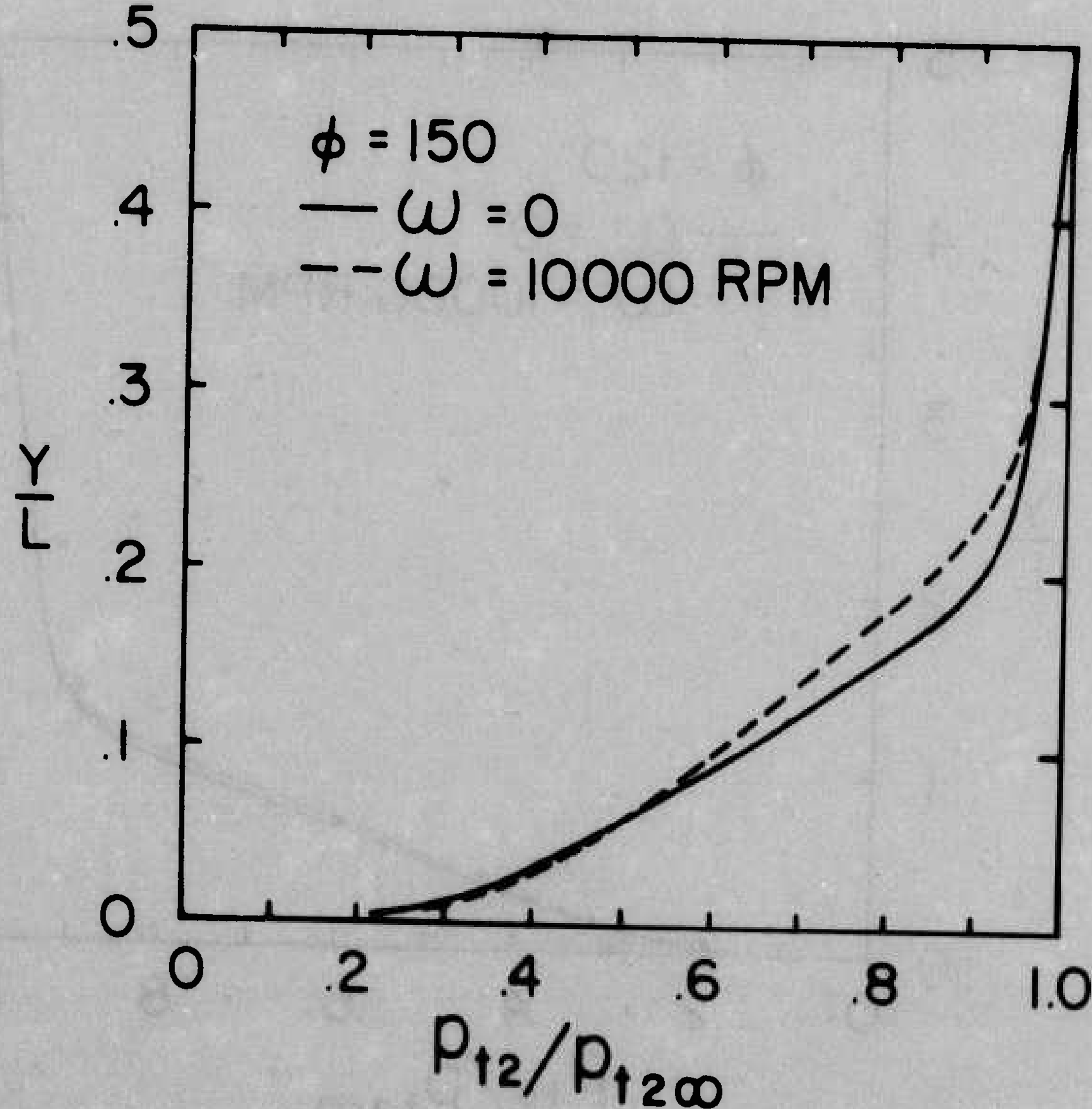


Figure 8. p_{t_2} Profiles, ϕ = 150

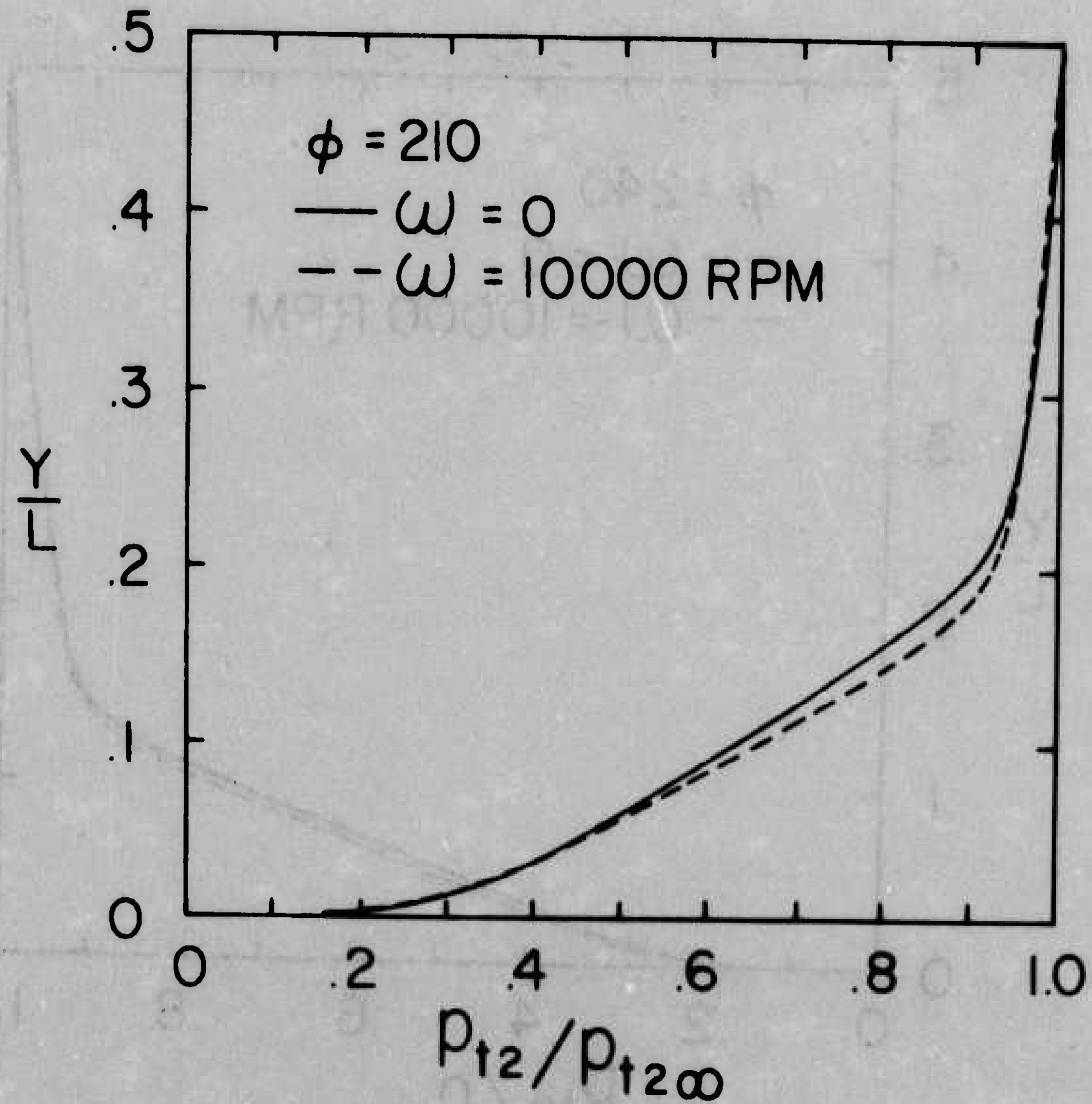


Figure 9. p_{t_2} Profiles, ϕ = 210

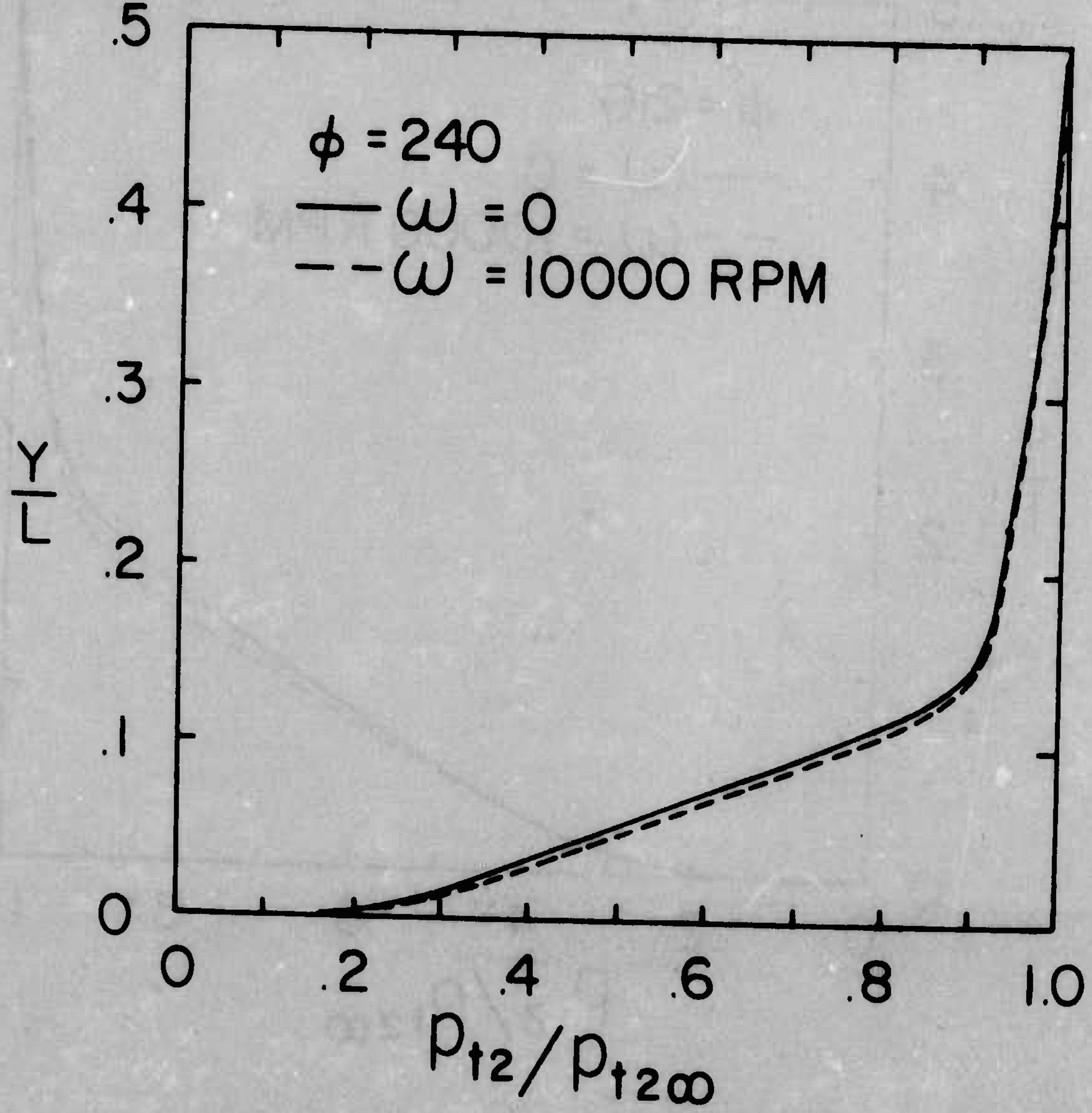


Figure 10. P_{t_2} Profiles, ϕ = 240

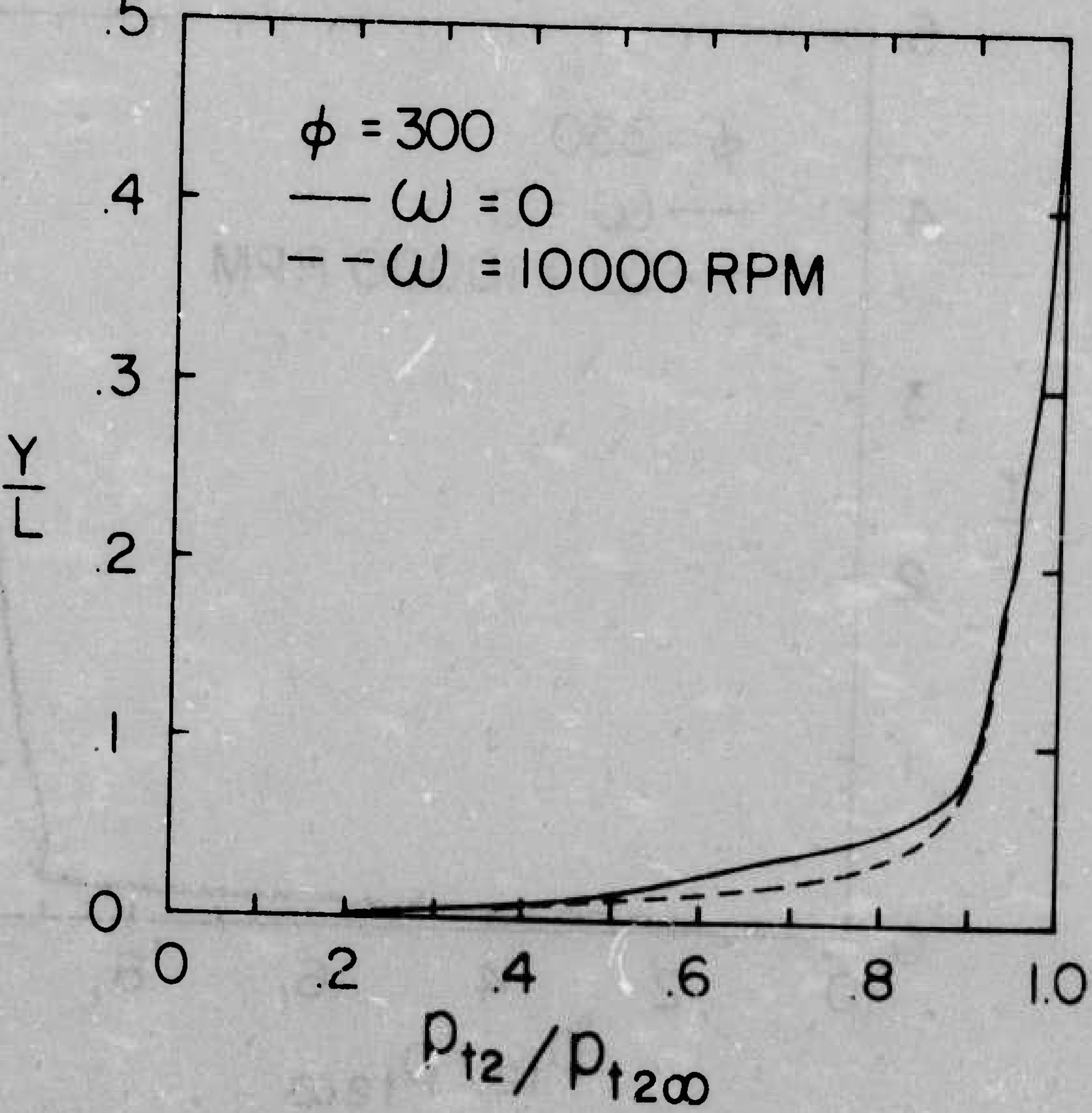


Figure 11. p_{t_2} Profiles, ϕ = 300

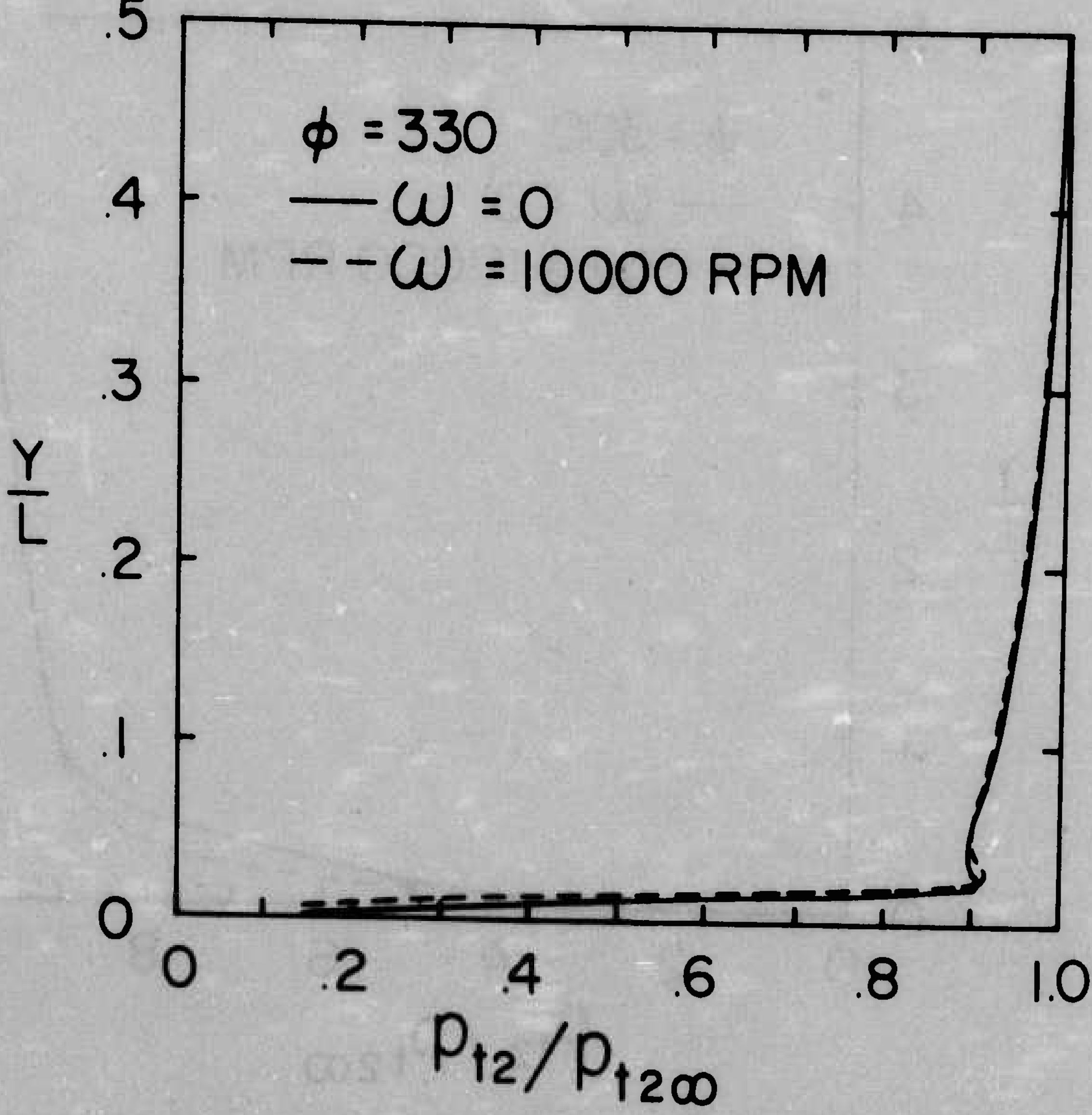


Figure 12. p_{t_2} Profiles, ϕ = 330

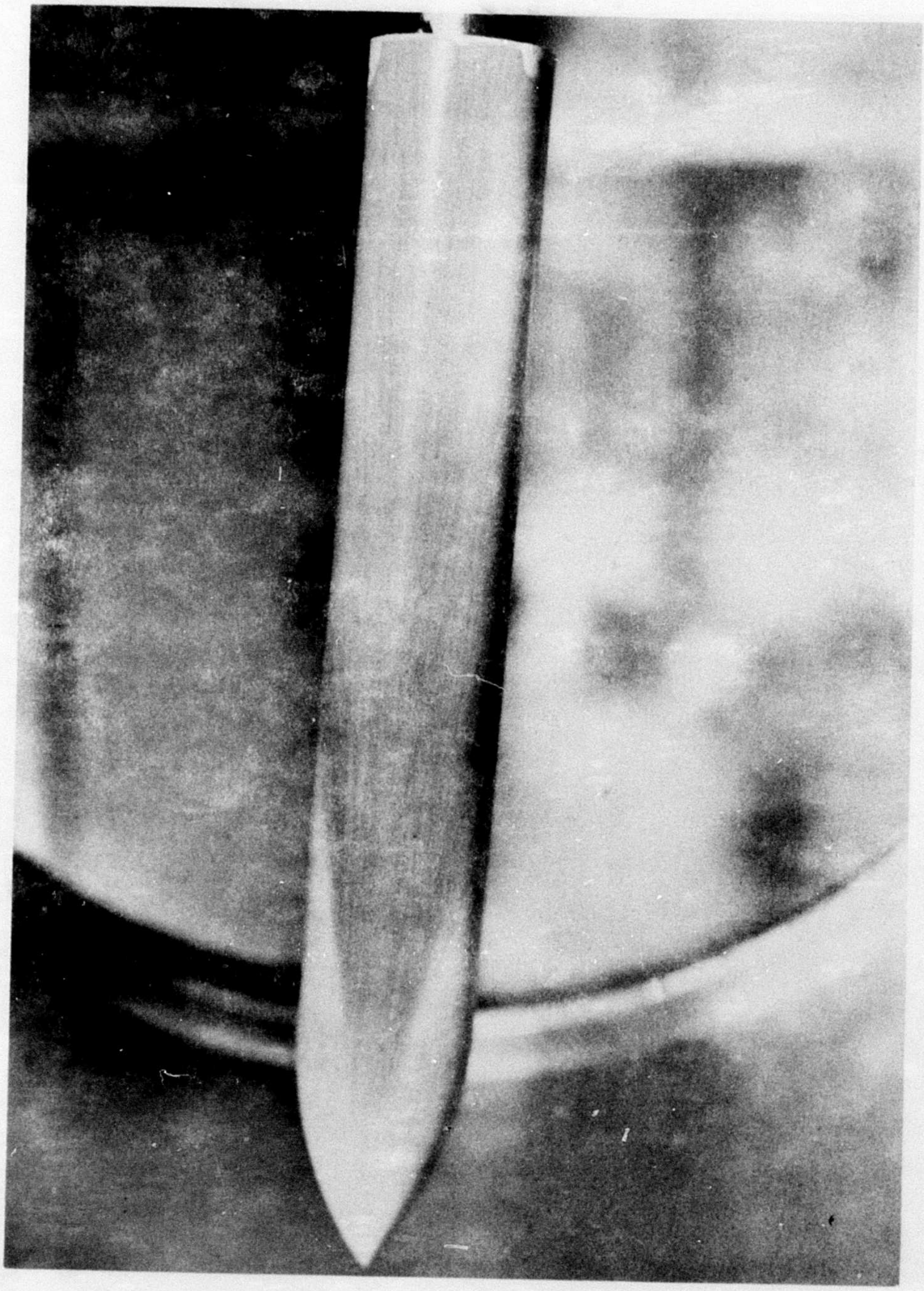


Figure 13. Oil Flow Pattern, $\phi = 0$

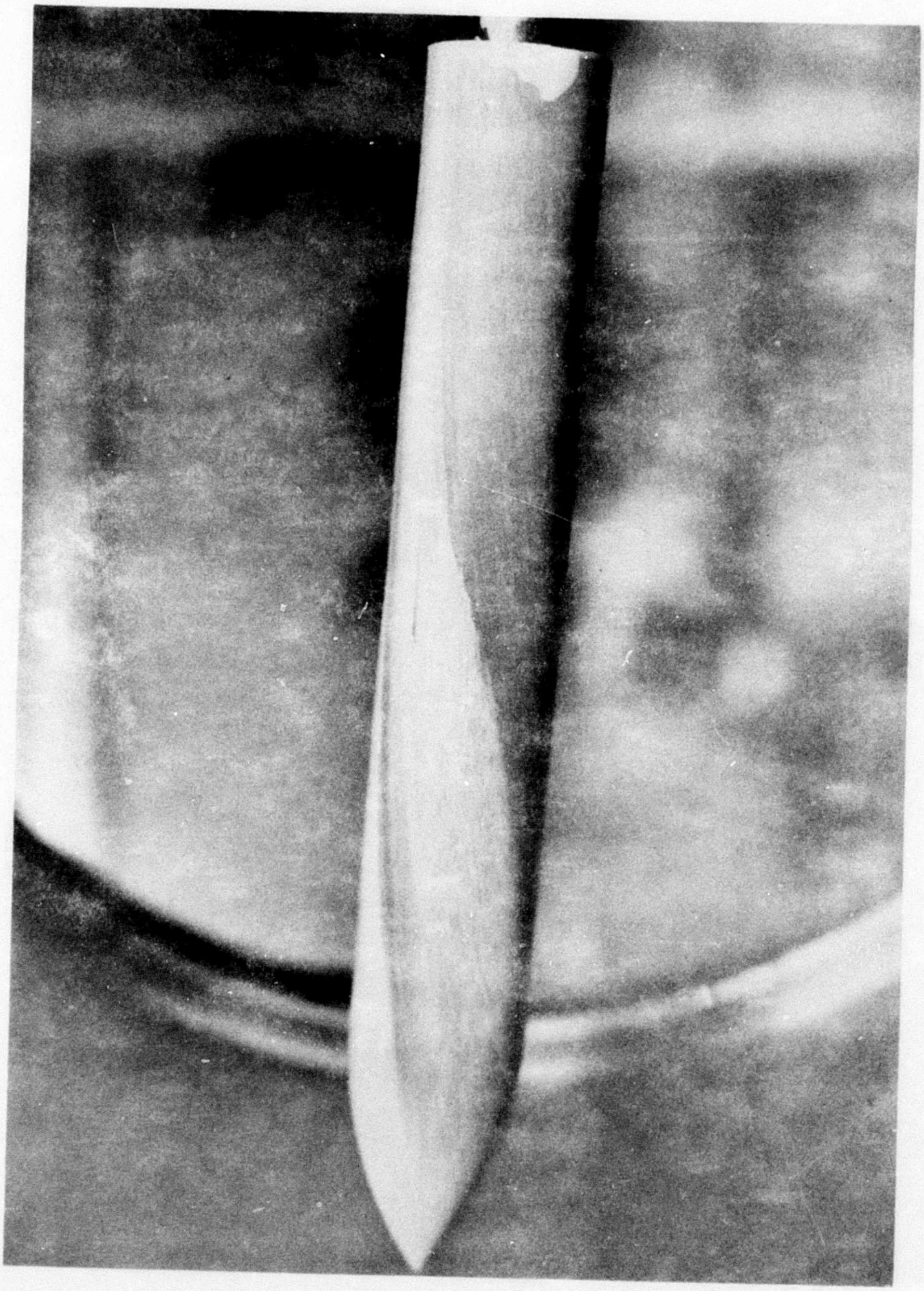


Figure 14. Oil Flow Pattern, ϕ = 90

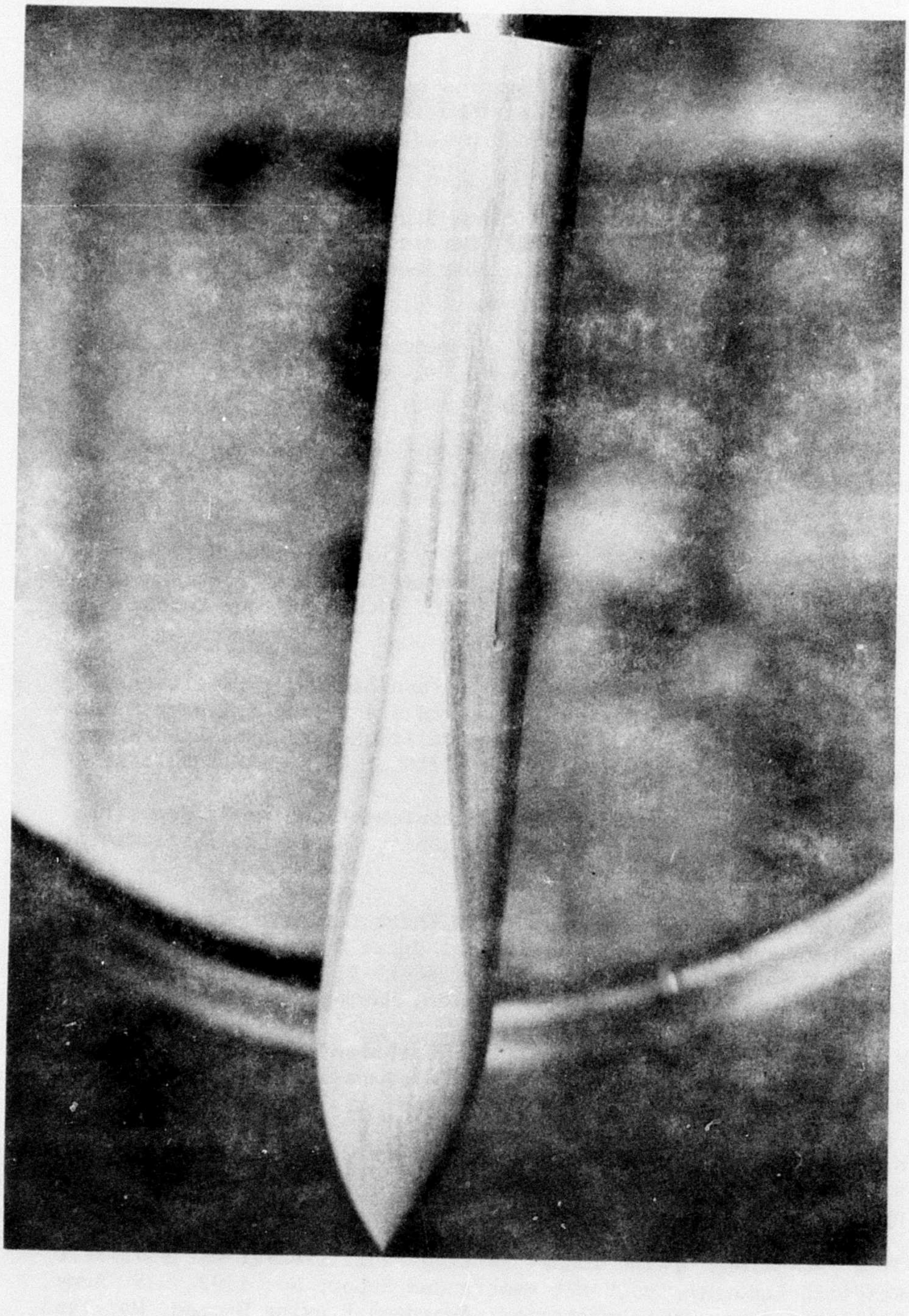


Figure 15. Oil Flow Pattern, ϕ = 180

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2. H. A. Dwyer, "Three Dimensional Flow Studies Over a Spinning Cone at Angle of Attack," BRL Contract Report No. 137, U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, February 1974. AD 774795.

3. H. A. Dwyer, "Boundary Layer on a Hypersonic Sharp Cone at Small Angle of Attack," *AIAA Journal*, Vol. 9, No. 2, February 1971, pp. 227-284.

4. T. C. Lin and S. G. Rubin, "Viscous Flow Over Spinning Cone at Angle of Attack," *AIAA Journal*, Vol. 12, No. 7, July 1974, pp. 965-974.

5. T. K. Fannelop and D. A. Humphreys, "A Simple Finite-Difference Method for Solving the Three Dimensional Turbulent Boundary Layer Equations," AIAA Paper No. 74-13, AIAA 12th Aerospace Sciences Meeting, January 1974.

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10. W. J. Rainbird, "Turbulent Boundary-Layer Growth and Separation on a Yawed Cone," *AIAA Journal*, Vol. 6, No. 12, December 1968, pp. 2410-2416.

11. J. C. McMullen, " Wind Tunnel Testing Facilities at the Ballistic Research Laboratories," BRL Memorandum Report No. 1292, U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, July 1960. AD 244180.

LIST OF SYMBOLS

p_{t_2} local total pressure behind a normal shock--sensed by total pressure probe

$p_{t_{2_\infty}}$ pressure sensed by total head probe at a position beyond the edge of the viscous boundary layer

ϕ azimuthal position, see Figure 3

Y coordinate perpendicular to model axis

L reference length, 2.54 cm

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